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Analysis of Field Test Results of the Injury Potential from a Variety of Blast Sources in Vented Enclosures

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During 1991 and 1992 a series of tests were conducted at the newly constructed Norwegian Defence Construction Service (NDCS) test facility at Terningmoen, Norway. The tests consisted of firing a variety of recoilless rifles from several enclosures and internal detonations of C-4. The study was divided into technical and medical sections. The technical section was designed to evaluate the propagation of overpressure waves in each of several enclosures. The medical section was designed to assess the risk of non-auditory injury in the enclosures, to provide data for validating injury predictive models, and to understand the biomechanical coupling process in a complex wave environment. Wall mounted overpressure gauges; animal mounted load gauges; and the blast test device (BTD) were used to measure the both overpressure environment and the load distribution on the body. The BTD consists of load gauges: four mounted on the chest and two in ear positions. During the initial phase of the study, eight shots were completed and a total of eight animals were exposed. During the remaining phase additional firings were conducted to validate a load predictive model (PC-based) under contract with Applied Research Associates (A.R.A.), and for prediction of injury due to the overpressure environment generated by recoilless rifles fired from enclosures.

Overpressure data from the each shot was analyzed with respect to the injury potential, as predicted by a first principal injury model developed under a US Army Medical Research and Development Command extramural contract by JAYCOR. These finding were correlated with gross pathologic finding and both external and internal measurements taken from the animal models. Calculations of chest wall velocity, chest wall motion, and accumulated lung work were made from the loading information and compared with measurements of internal pressure. This paper presents an analysis of the correlation between the prediction of injury, estimated from the loading information, with the actual observed gross pathological injury and correlations of chest wall dynamics with measured internal pressure. Predictions of the potential for non-auditory injury for the phase 2 tests were made and correlated with room size and weapon.

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Introduction

Non-auditory injury resulting from exposure to impulse noise is confined almost exclusively to the gas containing structures of the body (1,2,19,20,21). These organs include the upper respiratory tract, the lungs, and gastrointestinal tract. The lesions range from trivial surface petechial changes to tissue disruption and hemorrhage. Extensive work with simple freefield impulse noise environments has shown that the severity of injury to these susceptible organ systems is determined by some combination of the number of exposures, peak pressure, and A-duration (the time required for the overpressure to rise from ambient to its peak overpressure and return momentarily to ambient pressure) or A-impulse (the integral of peak pressure and A-duration) (4,6,12,13,14,19,21). This interaction of peak pressure, duration (or impulse) and number of exposures holds true only for Friedlander waves which are characterized by an instantaneous rise in pressure to a peak with a subsequent exponential decay. Predictions of primary blast effects to the lung have received the greatest attention because of the seriousness of its consequences. BOP induces pulmonary contusion similar to closed chest trauma which may occur in combat (i.e. as a result of soft body armor defeating projectiles) or in non-combat situations (i.e. from motor vehicle accidents). Damage to the lung may allow air emboli to enter the blood which can be a primary cause of prompt death from exposure. Decrease of pulmonary function is a debilitating consequence of BOP exposure and results in loss of exercise tolerance. In training, primary blast injury is a health hazard concern. In combat, pulmonary contusion injury is a combat casualty care concern. Neither Mil Std. 1474C or the Bowen curves adequately meet these needs. The former is not organ specific and is conservative for lung injury. The Bowen curves, on the other hand, give no guidance for repeated exposures and neither correlation adequately addresses complex wave environments. Accurate prediction is needed for both occupational exposure and for combat environments without being overly conservative.

Materials and Methods:

A blast overpressure test facility was constructed by the Norwegian Defence Construction Service (Forsvarets Bygningstjeneste) at Terningmoen, Elverum, Norway. This

facility houses an instrumentation trailer, office space, ammunition storage, a splinter plate (for characterizing the overpressure from weapons and explosives), a free field pad, and a variety of enclosures. They are capable of firing a variety of weapon systems (LAW, Carl Gustav, etc) or up to 3Kg of C-4. During phase I of the program, Swine were exposed to the complex blast waves generated from recoilless weapon's fire. Eight shots were completed during the study and a total of eight animals were exposed. The tests were conducted in the MG3 Bunker, the Carl Gustav Bunker, and a 33m^3 room with animals positioned at the gunner positions and a Blast Test Device (BTD) in the assistant gunner position. The MG3 bunker is 1.9 x 2.6 x 2.1m with two .27 x .20m firing ports 1.4m from the floor. For each of the tests in this structure the second firing port was closed (figure 1a). The Carl Gustav Bunker is .7 x 1.95 x 2.1m with a 1.95 x .7 x 2.1m firing ports in both the front and back walls (figure 1b). Because the Carl Gustav rifle is longer than the width of the bunker, the back blast was carried outside the bunker in shot 10. The position of the weapon was modified for shot 11, where the back of the Carl Gustav was positioned as far to the right as possible to ensure the breech was aimed at the rear wall of the enclosure instead of the opening in the back wall. This allowed the back blast from the weapon to discharge inside the bunker. The dimensions of the 33m^3 room are 4.7 x 3.0 x 2.4m, with a 1 x 1.5m firing port in the front wall (figure 1c). When the Carl Gustav was fired from this enclosure, the muzzle was positioned .10m inside the enclosure. A C-4 charge was also detonated in the geometric center of this room.

The swine used in the study had a mean body weight of 57.8 kg, which corresponds to the trunk weight of an average man. Each animal was anesthetized with intramuscular ketamine and suspended in a vertical orientation with respect to the ground. A pressure gauge was placed transnasally into the esophagus to the approximate center of the chest. The animal were maintained on a surgical plane of anesthesia with additional doses of ketamine. Euthanasia was accomplished 2 to 3 hours after the test with an overdose of barbiturate. The animals were necropsied and the pathology scored and tabulated. Ref ?

The BTD, placed in the assistant gunners position, was designed to simulate the placement of a body in the enclosure and allowed for measurement of blast load distribution on the body surface. The BTD's used in these studies were vertically mounted 700 x 300 mm cylinders on a wheeled tripod system (figure 2). Flush mounted on each of the cylinders were four (4) piezoresistive blast gauges, on an orthagonal coordinate system at 90 degree angles

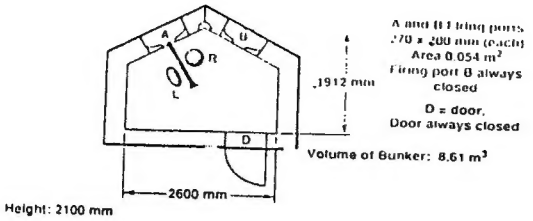

Figure 1a: Schematic of the Carl Gustav Bunker.

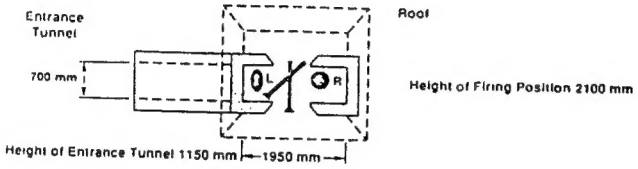

Figure 1b: Schematic of the MG3 bunker.

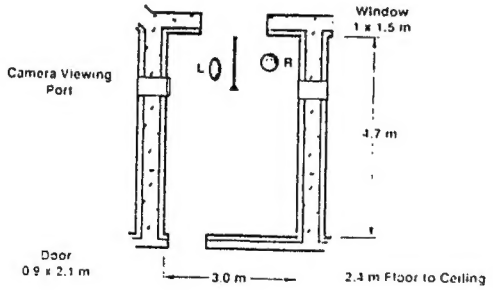

Figure 1c: A schematic of the 33m³ room.

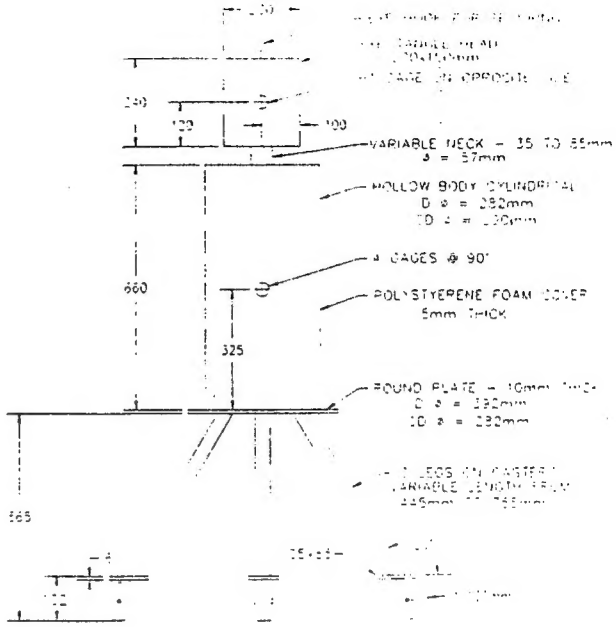

Figure 2: Schematic of the Blast Test Device.

midway on the length of the cylinder. On the top of each of the cylinders was mounted a rectangular cube with two gauges in ear positions.

During phase 2 of the program, data was taken for 51 shots in three enclosures using four shoulder fired weapon systems in each room. Dimensions for these rooms are presented in figure 3. Overpressure data used for this analysis were collected from the chest gauges of the BTD(s). The number of BTDs was dependent on how many soldiers are required to serve the weapon under test. The data from these sources should correspond to the overpressure field to which the soldiers would be exposed.

The digitized waveforms collected from the load gauges mounted on the BTD and the pressure gauges placed in the animals esophagus during for the phase 1 study were converted to a JIB file format using software designed by JAYCOR. Overpressure load measurements from the BTD's were imported into a first principle computer model currently being developed by JAYCOR Corporation.

Results:

Calculations were made of the chest wall acceleration, velocity, and displacement, From the data acquired from the BTD's in phase 1. A representative sample of the measured load and resultant calculated chest wall displacement time histories is presented in figure 4. The calculated chest wall displacement and a direct measure of esophageal pressure, from the same experiment, are overlaid in figure 5. The time base of the esophageal pressure data was shifted forward in time so the initial peaks would correspond. Deflections in the measured esophageal pressure are captured for the most part by the chest wall displacement calculations. Further calculations of the load data were made for the amount of work done on the lung parenchyma. The results were compared to a blast pathology database and predictions for percent number of expected injuries were calculated. The computational data was correlated with the actual pathology and the results are presented in Table 1. Except for a single test, the computational data shows good correlation with the pathological findings.

A worst case analysis was conducted for the data from phase 2 (Table 2). Predictions were made for the expected incidence of none slight, moderate, and severe pulmonary injury and for upper respiratory tract injury. This analysis was made for each room / weapon type

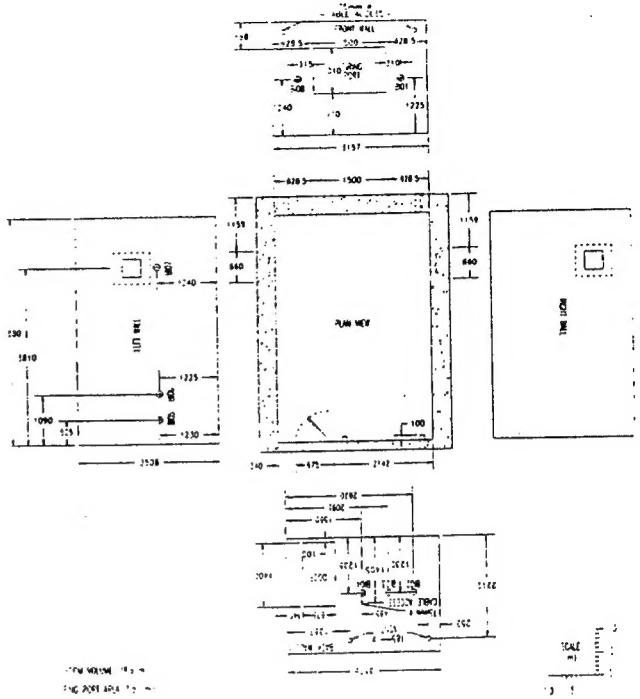

Figure 3: Schematic of Room B used during Phase Two.

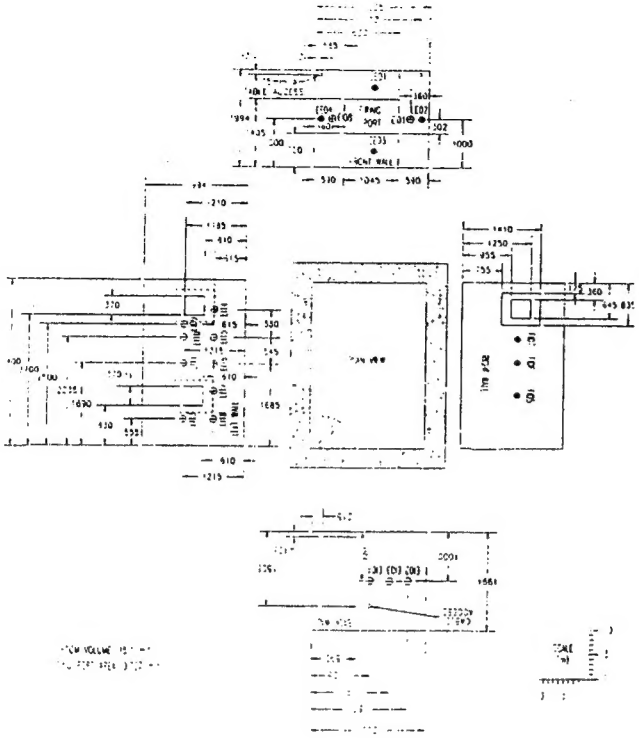

Figure 3 (cont): Schematic of Room E used during Phase Two

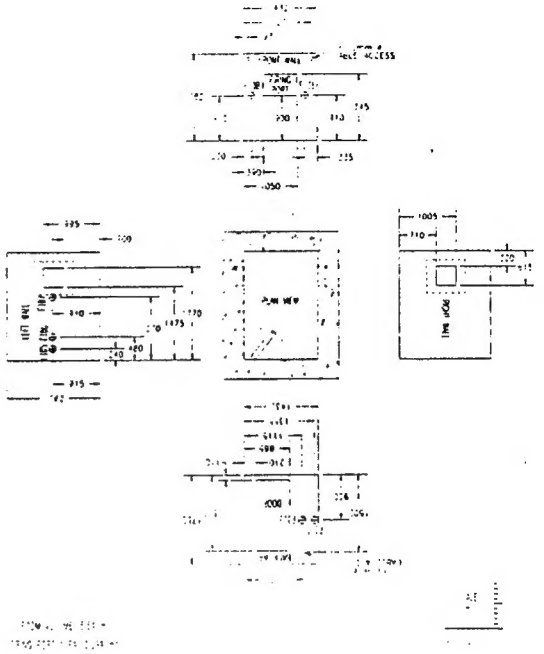

Figure 3 (cont): Schematic of Room F used during Phsae Two

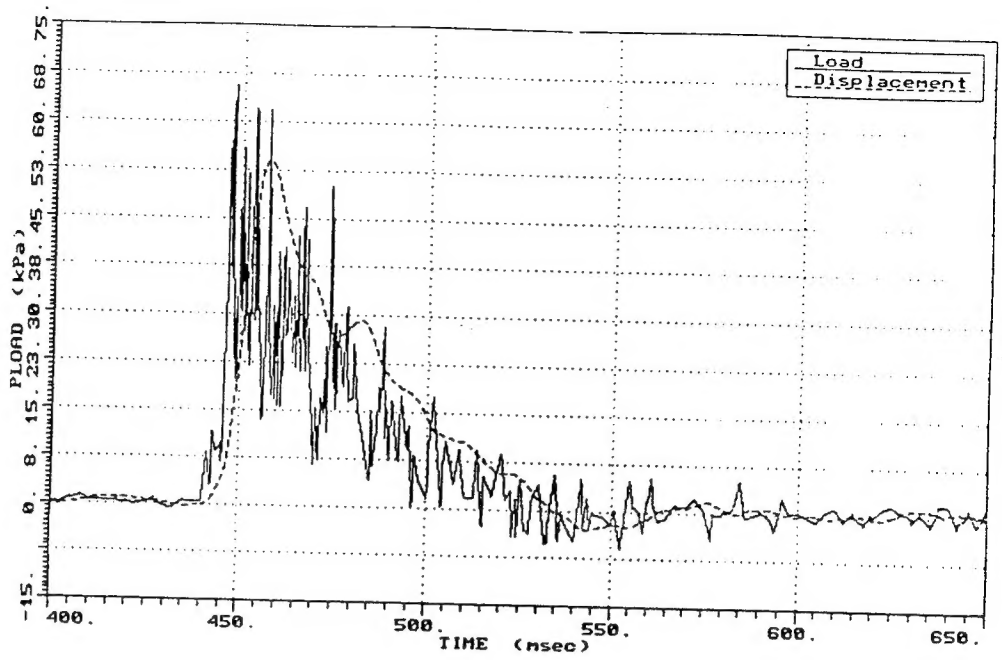

Figure 4: A representative sample of the measured load and resultant calculated chest wall displacement time histories.

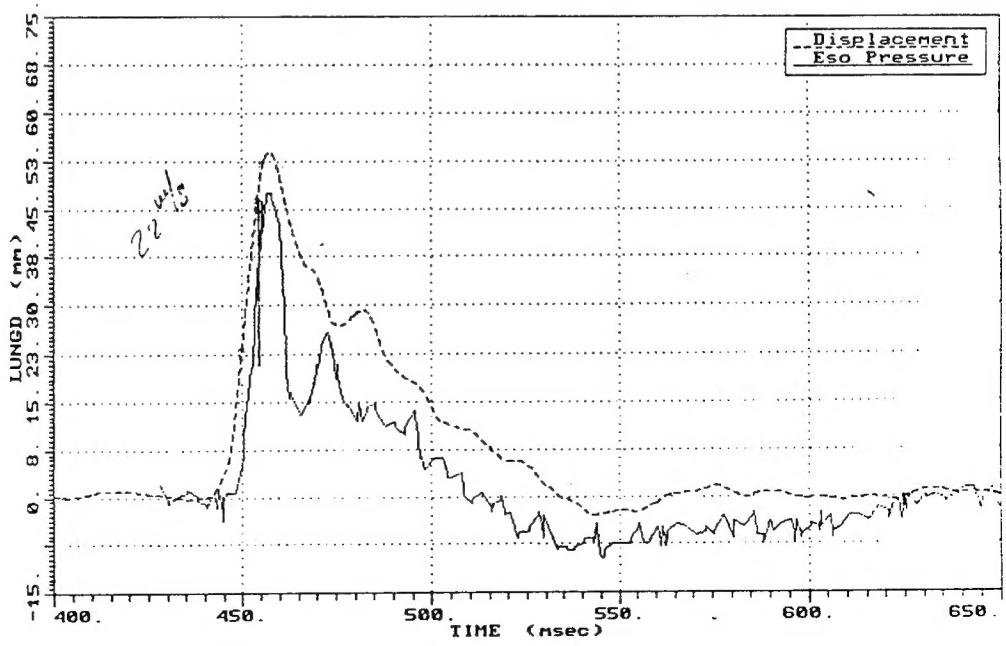

Figure 5: Calculated chest wall displacement actual measure of esophageal pressure acquired during the same experiment.

combination and assumes that the soldiers serving the weapon system are in an orientation most susceptible to the injury producing potential of the overpressure. Even though there were multiple firings of a weapon system in each of the rooms only the most injurious case is presented for each room / weapon type.

Table 1: Lung Work Calculations and Expected Percent Injured Correlated with Actual Gross Pathology

Test	Lung Work	Injury Prediction	Gross Injury*
1	5.394	334	None
2	1.212	4	Level 1
3	1.24	4	None
4	0.412	0	None
5	0.77	0	None
6	0.083	0	None
7	7.422	44	Level 4
8	1.633	7	Level 2

* None - No Injury
Level 1 - Minor Petechial Changes
Level 2 - Echymotic Changes
Level 3 - Difuse Echymosis
Level 4 - Extensive Lung Hemorrhage

Table 2: Results of Worst Case Analysis for Phase Two

Room #	M-72	NM-72	CARL GUSTAV	PZF3, DM18
B	100/0/0/0*	94/4/2/0*	89/7/4/0*	100/0/0/0*
38.6 c.m.	0% U.R.T Injury**	2% U.R.T Injury**	8% U.R.T Injury**	0% U.R.T Injury**
E	99/1/0/0*	84/10/5/0*	63/20/16/0*	100/0/0/0*
15.1 c.m.	4% U.R.T Injury**	25% U.R.T Injury**	74% U.R.T Injury**	0% U.R.T Injury**
F	97/2/1/0*	82/11/6/0*	36/25/36/2*	99/1/0/0*
5.54 c.m.	3% U.R T Injury**	44% U.R.T Injury**	96% U.R.T Injury**	7% U.R.T Injury**

* No Lung Injury / Slight Lung Injury / Moderate Lung Injury / Severe Lung Injury
** U.R.T. Injury = Upper Respiratory Tract Injury (Marker of Injury to more Sensitive Organ Systems

Discussion

Auditory injury from exposure to Blast Overpressure (BOP) has long been recognized as an occupational medicine problem. Exposure to BOP environments without adequate hearing protection can cause tympanic membrane rupture, pain, vestibular dysfunction, temporary threshold shifts, and some degree of permanent hearing loss (10,11). Until recently, these auditory effects had been the primary occupational medicine concern and the basis of current standards. However, in a military environment, with development of better hearing protection and more energetic weapon systems, the potential for injury to non-auditory structures has become a more important consideration. Occupational standards for exposure to simple freefield impulse noise environments are limited. Civilian occupational health standards are not well defined for exposure to ammunition or explosive hazards nor are they necessarily applicable to a military environment (5). Mil. Std. 1474C is the current United States Military Standard for occupational exposure to BOP. This standard is based on a relationship derived between peak overpressure, B-duration, number of exposures, and the type of hearing protection used (13).

Currently accepted injury criteria were derived from the Bowen lethality curves developed during the 1950's and 1960's by Lovelace Foundation researchers (1). These criteria characterize human lethality based on animal data 50% expected lethality and extrapolated for threshold lung injury and 1% expected lethality for a single exposure in one of three orientations (prone, side on, and against a single reflective surface). There are no provisions to determine the level of injury or injury potential for multiple exposures or complex wave environments. In developing the Bowen correlation for 50% lethality, over 2200 animals were exposure to nuclear style blast waves. A wide variety of species were employed and the blast conditions were largely limited to two geometrically simple cases: explosions of single charges in the freefield and blasts from shock tubes. Unfortunately, the database on primary blast injury from conventional munitions is much smaller. A wide range of injury levels and conditions have been studied, including free field explosions, repeated exposures, multiple explosions, and explosions within enclosures. Results of single exposure free field studies have been plotted against the Bowen curve for threshold lung injury. The results indicate that the Bowen curve is better correlated with severe injury (figure 6).

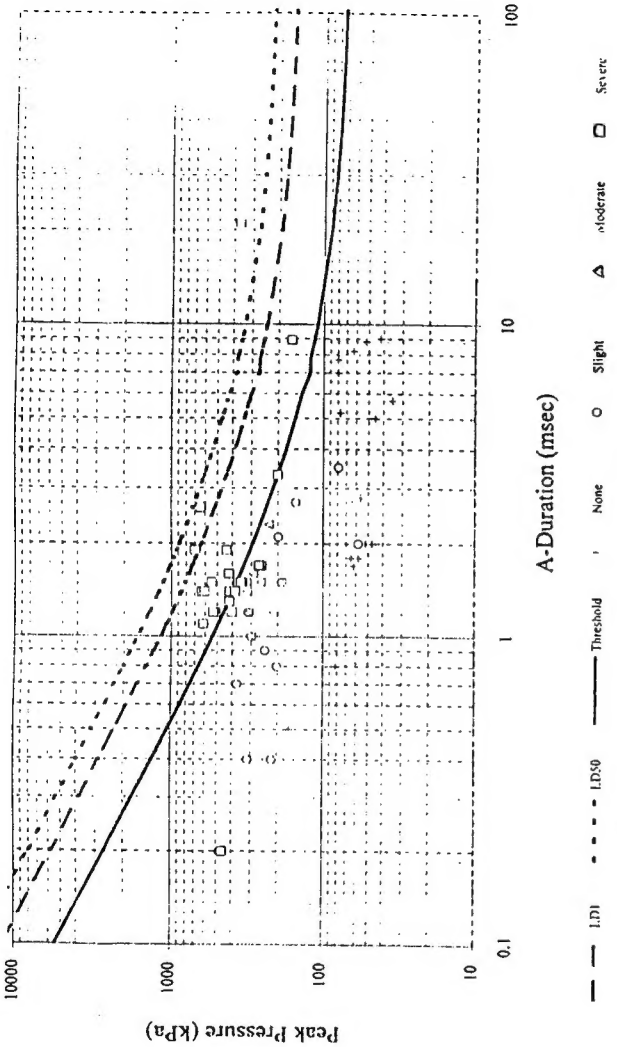

Figure 6: Plot of the peak overpressure vs duration injury scores for single exposure free field BOP exposure studies plotted against the Bowen curve for threshold lung injury.

** Mixing apples and pears?!

Complex pressure waves occur inside armored vehicles defeated by antitank rounds from detonation of explosives inside rooms, or from firing weapons from within enclosures. In a defeated armored vehicle, there is an initial fast-rising wave emanating from the point of penetration or detonation. Other shocks, emanating from the jet transversing the vehicle's interior, the exit site penetration and multiple internal reflections are superimposed on the primary overpressure. Additional blast events occur from detonation of other explosive devices or vaporized fuel and/or hydraulic fluid. For a detonation inside a room or from firing weapons from an enclosure there is an initial shock followed by multiple reflections from surfaces in the room. In both conditions, after several milliseconds, a 'quasi-static pressure might occur due to heating of the air and the accumulation of combustion products. The quasi-static pressure depends upon how rapidly venting occurs through breaks in the vehicle or room integrity. Widely accepted injury criteria have been developed for simple free field blast waves which can be defined in terms of peak pressure, A-Impulse and A-Duration (1,15). Extensive data to support injury criteria for complex wave environments does not exist. As a result, blast injury assessments inside reverberant spaces have been based on criteria developed for Friedlander blast waves (17). Although several methodologies have been suggested (absolute peak pressure/maximal 5 msec impulse technique, Richmond's partial impulse technique, etc.) none have proven satisfactory for all conditions (16). Based on the current understanding of the interaction between the body and blast waves, an "effective peak pressure" technique was developed for assessing injury in a complex blast wave environment (17).

As the body's interaction with complex blast waves has not been completely defined and extensive data to support a scientifically based complex wave criterion does not exist, the US Army Medical Research and Development Command (USAMRDC) has undertaken an extensive program to develop a modeling methodology, based on a mechanistic understanding of the injury process, for predicting non-auditory BOP injury in a variety of environments (freefield, repeated exposure, double peak, complex wave). Several theories have been presented to explain the mechanism of injury in blast overpressure environments. One theory is based on a understanding of blast wave impacting materials of differing acoustic impedance (3). They believe that stress, shock and shear waves are produced in the body as a result of blast wave interaction. The stress waves are defined as longitudinal pressure waves, similar to sound waves which produce small but rapid distortion of the tissue at interfaces with marked

differences in acoustic impedance. The shock waves produce an almost instantaneous high pressure wave fronts propagating through the body at much greater velocity than sound would normally travel through the tissue. Long duration, low velocity shear waves develop which cause gross distortions of the tissues producing asynchronous motion between adjacently connected structures as well as collision of viscera. The theory behind the model used for these analysis is based on a mechanical coupling process. A series of links has been established to translate blast conditions into injury. The blast wave reflects and evolves as it propagates outward from the source to the body. When the blast wave impacts with the body, a load is distributed on the surface, the magnitude of which depends on the body's shape and orientation. This external loading sets the body in motion producing rapidly changing internal stresses which are concentrated by geometric features of the affected organ and the boundaries between dissimilar materials. For example, when a blast load is applied to the chest wall, the chest wall is accelerated into the lung parenchyma inducing a local pressure/stress increase on the surface of the lung parenchyma. This rapid increase in pressure/stress is propagated into the lung parenchyma away from the motion of the chest wall, deforming the parenchyma in the direction of the stress. If the distortion remains within the elastic regime, the material will return to its original state and any work done by the stress will be recovered. When the applied stress exceeds the tensile strength of the parenchymal tissue, failure will occur. As the stress continues to increase or stress is maintained with time, the damage is caused by this excess stress or "irreversible stress." The work done on the tissue by this excess stress is called "irreversible work" and will not be recovered when the stress is removed (7,8,9,18).

The injury predictive model used for the analysis presented here is a single degree of freedom lung dynamics model which relates local compression of the lung to distortion of the pleural tissue (18). The model relates tissue distortion, generated by the compression wave established by the chest wall motion, to damage at the pleural surface which is then correlated to the amount of work done on the lung. If chest wall motion induces propagation of a pressure/stress wave in the lung parenchyma, then the timing of gross motion of the chest wall should correlate with the timing of the measured esophageal pressure peaks. The measurements of esophageal pressure peaks, allowing for a delay due to the wave speed of the lung parenchyma, show good correlation the calculated gross displacements of the chest wall. Except for one test, the predictions of injury for the phase I tests also demonstrate good

correlation with actual gross pathology. URT injury has been shown, in the free field, to be a precursor of injury to other more sensitive organ systems (6). The computer model, using a mechanistic approach which incorporates an understanding of laryngeal biomechanics, calculates the degree of localized tissue stress caused by BOP exposure. This calculated stress value is compared to the stress required to induce laryngeal capillary rupture and a database of the incidence of BOP induced URT injury in order to make a prediction of the incidence of expected injury (18). It is reasonable to assume from this analysis that the injury predictions made from the model, within some statistical variation, are an accurate representation of the BOP hazard to soldiers firing the recoilless rifles from the enclosures tested in this study. However, continued validation of the computer model predictions of injury is critical for its final acceptance as a valid technique for injury prediction.

The analysis in this paper is limited to only the BOP hazard to soldiers firing recoilless rifles from within enclosures. There are additional hazards the soldier may be exposed to which may be more life threatening or debilitating than the BOP hazard. For example, the PZF3, while producing the lowest overpressure in any of the rooms, did produce extensive amounts of smoke, dust, debris, and combustion products which should be analyzed. Such an analysis will most likely elucidate an alternate injury mechanism for this system and may preclude its firing from enclosures.

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MABS 13 PAPER
MODIFICATION OF HIGH EXPLOSIVES TO MATCH NUCLEAR SHOCK LOADING

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Introduction

In the air, detonation of high explosive (HE) charges produces pressure waveforms that are qualitatively similar to nuclear events. At lower overpressures the agreement between HE and nuclear is quite good. However, this is not true at the higher levels because of the proximity of the HE contact discontinuity behind the shock front. Moreover, the pressure waveform has a flat topped appearance with a backward facing shock which differs from the triangular peaked nuclear waveform.[1] On the ground, shock waves produced by high explosive detonations cannot provide the necessary impulse, because of limitations in size and cost, for simulating the ground shock effects of near surface nuclear bursts. As a result, techniques of simulation have been driven to modify the high explosive source in order to better "match" the nuclear loading conditions.

We have found that numerical simulations suggest many ways to make the HE overpressure waveforms agree more with nuclear, both for the airblast and the ground shock. For example, design of the charge placement can modify the waveform at the high overpressure levels.[2] Additionally, the front part of the HE waveform can be modified by wedges to produce a Mach stem.[3] The high explosive itself can be modified by dilution with foam or other inert materials. It may be encapsulated or sandwiched with inert liquids in order to better match impulses. Combining different HE of varying energy levels can also be utilized for optimization.

Using detailed computations to predict the airblast generated from HE charge including modeling the unsteady detonation wave as it travels through the HE, we have developed a robust methodology for identifying the areas where HE modification can produce good agreement with nuclear waveforms. Variations in charge geometry, charge density and container influence have been investigated using the P.C. based wave propagation codes. Concave and convex wedges have been used to obtain a shock structure that matches not only the front part of the nuclear waveform but also the rear portion.

Event Phenomenology

Airblast and ground shock are major damage mechanisms from nuclear detonations. Concern over survivability and vulnerability produce requirements for testing in the nuclear environment. Condensed high explosives have been shown to be the most versatile in simulating airblast and ground shock.

Differences in pressure waveform shape and impulse[2] can be overcome by appropriate use of geometry in charge placement. Encapsulation of high explosive charges by liquids can afford an inexpensive approach to waveform modification. Combined effects[4] which include ground shock from direct coupling and surface airblast can be simulated with hybrid high explosive configurations.